LCA Case Studies

Life Cycle Assessment of Water Production Technologies

Part 2: Reverse Osmosis Desalination versus the Ebro River Water Transfer

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Preamble. This series of two papers analyses and compares the environmental loads of different water production technologies in order to establish, in a global, rigorous and objective way, the less aggressive technology for the environment with the present state of the art of technology. Further, an estimation of the potential environmental loads that the considered technologies could provoke in future is also presented, taking into account the most suitable evolution of the technology. **Part 1**[1] presents the assessment of most commercial desalination technologies which are spread worldwide: Reverse Osmosis, Multi Effect Desalination and Multi Stage Flash. **Part 2** presents the comparative LCA analysis of a big hydraulic infrastructure, as is to be found in the Ebro River Water Transfer project, with respect to desalination.

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Abstract

Intention, Goal and Background. In this paper some relevant results of a research work are presented, the main aim of which consists of performing the environmental assessment of different water production technologies in order to establish, in a global, rigorous and objective way, the less aggressive technology for the environment for supplying potable water to the end users. The scope of this paper is mostly oriented to the comparative Life Cycle Assessment of different water production technologies instead of presenting new advancements in the LCA methodology. Based on the results obtained in Part 1 (LCA of most widespread commercial desalination technologies), the particular case of a big hydraulic project, which is the Ebro River Water Transfer (ERWT) considered in the Spanish National Hydrologic Plan, versus the production by desalination of the same amount of water to be diverted, is compared in Part 2. The assessment technique is the Life Cycle Analysis (LCA), which includes the entire life cycle of each technology, encompassing: extraction and processing raw materials, manufacturing, transportation and distribution, operation and final waste disposal.

Methods and Main Features. The software SimaPro 5.0, developed by Dutch PRé Consultants, has been used as the analysis tool, because it is a well known, internationally accepted and validated tool. Different evaluation methods have been applied in the LCA evaluation: CML 2 baseline 2000, Eco-Points 97 and Eco-Indicator 99. Data used in the inventory analysis of this Part 2 come from: a) desalination: data obtained for existing plants in operation; b) ERWT: Project approved in the Spanish National Hydrologic Plan and its Environmental Impact Evaluation and; c) data bases implemented in the SimaPro software – BUWAL 250, ETH-ESU 96, IDEMAT 2001.
Different scenarios have been analyzed in both parts in order to estimate not only the potential of reduction of the provoked environmental loads with the present state of the art of technology, but also the most likely future trend of technological evolution. In Part 1, different energy production models and the integration of desalination with other productive processes are studied, while the effect of the most likely technological evolution in the mid-term, and the estimation of the environmental loads to the water transfer during drought periods are considered in Part 2.

Results and Discussion. As proven in Part 1, RO is a less aggressive desalination technology for the environment. Its aggression is one order of magnitude lower than that of the thermal processes, MSF and MED. The main contribution to the global environmental impact of RO comes from the operation, while the other phases, construction and disposal, are almost negligible when compared to it.
In the case of the ERWT, the contribution of the operation phase is also the most important one, but the construction phase has an important contribution too. Its corresponding environmental load, with the present state of the art of technology, is slightly lower than that provoked by the RO desalination technology. However, the results obtained in the different scenarios analyzed show that the potential reduction of the environmental load in the case of the ERWT is significantly lower than that in the case of the RO. The effect of drought periods in the assessed environmental loads of the water transfer is not negligible, obtaining as a result an increasing environmental load per m^3 of diverted water.

Conclusion. The environmental load associated with RO, with the present state of the art of technology, is slightly higher than that provoked by the ERWT. However, considering the actual trend of technological improvement of the RO and the present trend of energy production technology in the address of reducing the fossil fuels' contribution in the electricity production, the environmental load associated with RO in the short mid-term would be likely to be lower than that corresponding to the ERWT.

Recommendations and Outlook. Although desalination technologies are energy intensive and provoke an important environmental load, as already explained in Part 1, they present a high potential of reducing it.
In respect to ERWT, the results indicate, when the infrastructure of ERWT is completed (by 2010–2012), that the LCA of RO will be likely to be against the water transfer. With the present technological evolution of water production technologies and from the results obtained in this paper, it seems, from an environmental viewpoint, that big hydraulic projects should be considered the last option because they are rigid and long-term infrastructures (several decades and even centuries of operation) that provoke important environmental loads with only a small margin for reducing them.

Keywords: Comparative life cycle assessment; desalination; Ebro river water transfer (ERWT); multiple effect distillation (MED); multiple stage flash (MSF); reverse osmosis (RO)

[1] Raluy RG, Serra L, Uche J (2005): LCA of Different Commercial Desalination Technologies (MSF, MED, RO). Int J LCA 10 (4) 285–293

1 Introduction

Water resources per capita in Spain are about 2,775 m^3/year, but their distribution is not homogeneous, neither in time nor geographically. There are some regions of Spain with a clear water scarcity, basically the Mediterranean region and the Balearic and Canary Islands in the summer period, in which the touristy pressure, and the high consumption of water in agriculture (irrigation) coincide. In order to solve the water scarcity in Spanish Mediterranean areas, the Spanish National Hydrologic Plan (SNHP) was approved in July 2001, in which the water abstraction of 1,050 hm^3/year from the Ebro River to the Mediterranean regions is considered. Desalination can be considered an alternative source of fresh water supply in order to cover the water scarcity in those regions. However, this option has been discarded arguing, among other reasons, that it is an energy intensive technology provoking a very important environmental impact.

A comparative evaluation of the environmental loads provoked by the water transfer versus the water supply by RO desalination is presented in this Part 2, which is the desalination technology provoking the lowest environmental load as shown in Part 1, of the same amount of diverted water.

It is important to remark that it is very difficult to establish a comparison between water desalination technologies and the water transfer of a river, because the former increases the water resources and the later represents a tool that only redistributes existing water resources. However, both technologies can be considered water supply techniques for the receiving basins that are lacking fresh water.

The structure of this second part is the next. First, the main characteristics of the Ebro River Water Transfer are briefly described. The most relevant features of the desalination technologies, including those of the Reverse Osmosis (RO) desalination technology, have already been explained in Part 1. However, some specific features considered in the comparative analysis are described in Section 3. Then, the main results are presented, including a sensitivity analysis corresponding to different scenarios in order to estimate the most likely future trend of environmental loads associated with each technology as an energy production evolution. Finally, the main conclusions achieved are briefly commented upon.

2 Ebro River Water Transfer (ERWT)

It is the most important hydraulic construction of the recent Spanish National Hydrologic Plan (SNHP), approved by law on July 5th of 2001 (the only way to perform interbasin transfers in the Spanish Hydrologic planning framework). Its technical support can be found in the five volumes of the Draft Bill of the SNHP, edited in September 2000 by the Spanish Ministry of Environment [1], based in turn on the Spanish Water White Book [2], once the Hydrological Plans of the Spanish Basins had totally been approved.

The transfer is considered in the Draft Bill of the SNHP as the only and the most economic alternative to correct the water imbalance between different hydrologic basins. The maximum volumes of water that can be diverted (presumably from October to May, in which the flow regime of the Ebro River permits water abstraction) are:

- 190 hm^3 for the Inland Basins of Catalonia (Barcelona area),
- 315 hm^3 for the Júcar Basin (Valencia Autonomous Community),
- 450 hm^3 for the Segura Basin (Murcia Autonomous Community and Alicante province),
- 90 hm^3 for the South Basin (Almería province).

The total volume to be diverted is 1,050 hm^3/year, which is reduced to 1,000 hm^3/year[1] due to the effect of leaks and evaporation (most of the water transfer is an open channel). The ERWT has two paths, the north-path to the Inland Basins of Catalonia (IBC) for the urban supply to Barcelona, and the south-path to Levante with 860 hm^3/year, for agricultural and urban uses and containing the next detractions (see **Fig. 1**):

- 84 hm^3/year to the Castellón province (21 to the northern area, 42 nearby Castellón city and 21 to the southern area)
- 63 hm^3/year to the Tous Reservoir area (Valencia province)
- 168 hm^3/year derived in the Villena destination (Alicante province)
- 42 hm^3/year raised to the Altiplano de Jumilla-Yecla (northeast of Murcia province)
- 341 hm^3/year allocated to the Segura Basin
- 84 hm^3/year conducted through the right margin channel of the Tajo-Segura aqueduct to the Almanzora Cave Reservoir (Murcia and Almería provinces)
- 79 hm^3/year for the final section to Aguadulce (Almería province)

[1] From the specified 1000 hm^3/year, 560 of them are proposed for irrigation (to remove the over-exploitation of aquifers and guarantee the Levante irrigated surfaces), and the rest (440 hm^3/year) are destined for urban consumption.

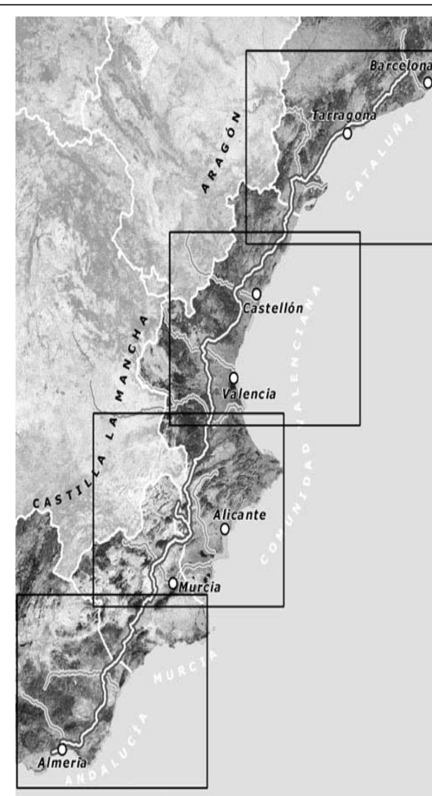

Fig. 1: South-path of the ERWT to the Levante region proposed by Trasagua [3]

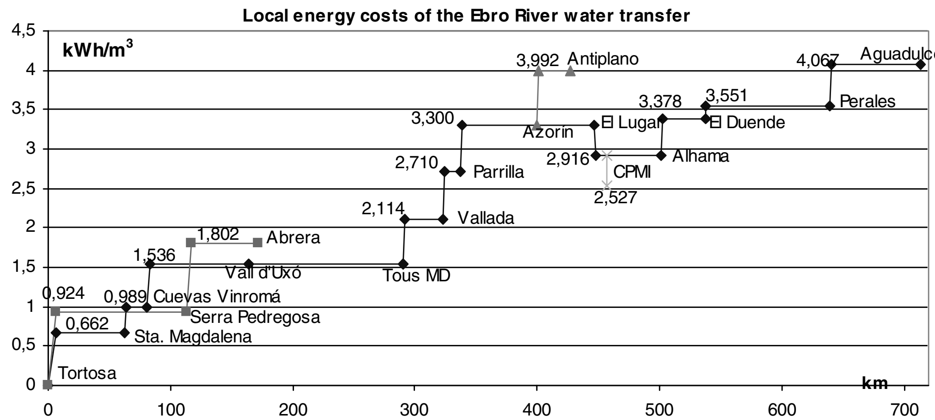

Fig. 2: Ebro transfer profile and the corresponding energy consumption at each destination [3]

The approximate length of the project at present [3], which has suffered from important modifications since the first attempt proposed in the Draft Bill of the SNHP in order to avoid larger environmental troubles in ZSPBs (Zones of Special Protection for Birds) and PCIs (Places of Community Interest), is about 172 km in the northern route and 742 km in the southern route. Most of them are open channels, except the final route in the Provinces of Barcelona and Almería, with lower flow volume, and buried pressure pipelines. The sharp profile of the southern route (see **Fig. 2**), requires the construction of large tunnels, aqueducts, siphons, and pumping stations for its construction, with their economic and added environmental costs. The LCA analysis of Ebro River Water Transfer presented in this paper is based on the basic documentation contained in the Transfer Project and its Environmental Impact Study [3], where the 'typical' hydraulic infrastructures as a function of the flowing volume are described. Although these documents do not describe the project in detail, and present some lack of definition with respect to the definite project and its construction, they present enough information for doing a general comparative analysis and LCA assessment of this type of technology.

3 Objective and Scope of the Analysis

The main objective of this study consists of obtaining and estimating the environmental loads associated with the ERWT and the desalination with RO of the same amount of diverted water, in order to determine, from global perspective, the technology provoking less environmental damage. The selected desalination technology is RO because, as shown in Part 1, its environmental load is about one order of magnitude lower than that associated with the MSF and MED technologies.

3.1 Functional unit

The considered functional unit in the analysis is 25,000 hm^3, which is the result of supplying 1,000 hm^3/year fresh water during 25 years of operation. This is the maximum amount of water that the Spanish Mediterranean regions are going to receive from the ERWT during 25 years. Two different repayment periods have been considered for the hydraulic work: 25 years and 50 years (as usual), taking into account the expecting life of the desalination alternative.

In the case of desalination, it has been considered that the fresh water could be obtained from 65 desalination plants producing, on average, 45,500 m^3/day and operating 8,000 hours per year. The amortization period considered for the desalination plant is 25 years of useful life, taking into account that the membrane replacement, considering a conservative scenario as already explained in Part 1, will be made every 5 years.

3.2 System limits

The aspects that have been taken into account in the analysis and those that have been discarded are listed next, in order to get a more precise idea of the scope of the study. In general, the input of materials has been considered in the construction stage and the input of energy has mainly been considered during the operation of both analyzed systems. Moreover, the same cut-off criteria applied in the first part of the paper have also been taken into account in this Part 2.

Table 1 shows the aspects that have been considered and those that have been omitted.

Note that the aspects that have been considered are those related to the materials and energy required for building, operating and dismantle the water systems (RO plants and water channel). However, very important aspects have been omitted due to the lack of relevant data. Among others, the next examples can provide an idea of the importance of the not considered effects.

For instance, the extraction of the water resource in the Ebro River basin is not considered. This effect would have a non-negligible environmental impact in the Delta of the Ebro River. A specific plan for protecting the ecosystem of the Delta of Ebro River from the saline intrusion provoked by the reduction of the Ebro River Water flow rate was considered, but the previously referred plan was not made at the moment of performing this analysis.

Another important aspect not included in the analysis is the effect on biodiversity of both alternatives. In the case of the ERWT and in the specific case of the Iberian Peninsula, the connection of different water basins could provoke an important loss of biodiversity [12]. Spanish basins have been formed about 25 million of years ago and they have remained isolated for millions of years. This effect has allowed the development

Table 1: System Boundaries

	RO Desalination	ERWT
Have been included	Constructive data: pieces of equipment, and construction materials of the plant components (including their transport) and their manufacturing processes	Ground removal and its transportation to an average distance of 50 km far away [1]
	Operation and maintenance	Channel construction (different topologies)
	A pipeline of 20 km from each RO plant for the desalted water distribution	Operation
	Dismantle and final disposal (without considering any recycling)	All infrastructures (channels, pipes, aqueducts and so on) are totally new [2]
	Quality of desalted water fulfils the legal requirements for human consumption [3]	
	4 kWh/m^3 of net energy consumption [4]	2.5 kWh/m^3 of net energy consumption [5]
		Two different repayment periods, 25 and 50 years
Have not been included	Brine disposal effects (fauna and flora) [6]	Environmental impact in the Ebro River basin (Ebro Delta)
	Product chemicals disposal (water pre-treatment, post-treatment, and so on) [7]	Biological effects [8]
	Noise effect	Water treatment [9]
		Secondary water distribution network [10]

1 Only the ground removal corresponding to the volume of the channel required for the water transfer has been considered. The ground removal provoked by the auxiliary systems and the constructions has not been taken into account due to the lack of reliable data.
2 It is assumed that, even though plans have been made to use some already existing infrastructures (more than the 30% of the projected length according to Trasagua [3]). This approach has been considered because all of them need to be enlarged to support the required volumes of water proposed by this transfer.
3 These requirements are established by the European Directive 98/83/CEE and by the World Health Organization. It is also considered that desalted water can be used in agriculture and for most industrial applications without any additional treatment.
4 This consumption is considering the present state of the art of the technology for big plants with a Pelton turbine as an energy recovery system [4,5]. However, the fast technological development of this technology indicates that this amount will be significantly reduced in the short mid-term. Nowadays, small RO plants with an energy consumption of about 2 kWh/m^3 already exist [6,7].
5 This value can be considered optimistic because a detailed evaluation of the water pumping required establishes a net energy consumption of about 2.7 kWh/m^3 [8].
6 At present, this is a matter of active research and when this study was performed reliable data with regard to this were not available. However, some research studies already published [9–11] indicate that the brine disposal damage is not very important if compensatory measures are taken.
7 Their amount is very small with respect to the seawater, brine discharge and permeate flows.
8 Effects associated with the rupture of the Hydrological Basin Unit, which can reduce the biodiversity and can provoke the loss of endemic species [12], for instance the invasion of the Zebra mussel of Mediterranean basins [13]
9 Water whose salinity is currently about 800 ppm, for many of its possible applications.
10 From the channel to the end-users, because there is not any available information in the Transfer Project presented by the Spanish Government [3].

of several species of endemic fauna, which are unique and specific of the Iberian Peninsula. It is very likely that the connection of different water basins will endanger the existence of those endemic species [12]. Furthermore, the transmission of pollutants and invasive species, as is the case for the Zebra mussel, will be highly facilitated [13]. In this context, the effect of brine disposal on biodiversity, particularly its impact on the *Posidonia Oceanica*, which is a protected species in the Spanish Mediterranean coast, has not been included because it is not well known yet and should be carefully analyzed [9].

However, despite the important non-considered effects, the obtained results presented in the next section are relevant enough for achieving interesting trends and conclusions.

4 Results

This section presents the results of the LCA comparison of RO and ERWT. Moreover, the results corresponding to three different analyzed scenarios are also included (parametric studies):

- expected technological improvement of the RO technology in the short and mid term,
- evolution of the electricity production models in the mid or long term,
- the effect of transferred water volumes in drought periods.

The reason of these studies is that the water transfer is a civil work with a long-term scope of several decades and even centuries. It is intended that it would provide water to some Spanish Mediterranean regions in the mid and long-term. Thus, in these conditions it has been considered that it is necessary to estimate, as accurately as possible, the future environmental loads of both alternatives with a mid and long-term perspective (subsections 4.1.1–4.1.3).

4.1 LCA of RO and ERWT

Table 2 shows some of the most important materials required for both analyzed alternatives. The detailed inven-

Table 2: Most relevant materials of the RO plants required for desalting 1,000 hm^3/year of fresh water and for building up the ERWT

Material	RO Desalination (ton)	ERWT (ton)
Cement	–	1,240,000
Concrete	130,000	–
Reinforced concrete	48,750	8,400,000
Iron	650	–
Steel	87,750	1,052,000
Stainless steel 316L	370	–
Gravel	-	16,555,000
Sand	65,000	4,520,000
Aromatic polyamide	370	–
Epoxy resin	23	–
Polyethylene	–	16,000

Table 3: Relevant airborne emissions produced by RO for different energy consumptions and ERWT

	RO (4 kWh/m^3)	RO (3.5 kWh/m^3)	RO (3 kWh/m^3)	RO (2.5 kWh/m^3)	RO (2 kWh/m^3)	ERWT (50 years)	ERWT (25 years)
kg CO_2 / m^3 produced water	2.26	1.99	1.73	1.46	1.20	1.44	1.55
g dust / m^3	3.10	2.72	2.37	1.95	1.56	2.02	2.03
g NO_x / m^3	5.10	4.50	3.92	3.33	2.74	3.58	4.21
g NMVOC / m^3	1.00	0.88	0.76	0.64	0.52	0.77	0.93
g SO_x / m^3	14.7	13.28	11.86	10.49	9.08	7.25	7.53

Table 4: Overall LCA scores for different energy consumptions of RO and ERWT (25 and 50 years of repayment periods). The calculus base is 25,000 hm^3 fresh water for both systems

	Unit	RO (4 kWh/m^3)	RO (3.5 kWh/m^3)	RO (3 kWh/m^3)	RO (2.5 kWh/m^3)	RO (2 kWh/m^3)	ERWT (50 years)	ERWT (25 years)
EI 99 [1]	GPts	2.62	2.33	2.04	1.75	1.46	1.86	2.20
Ecopoints 97	GPts	43,400	38,800	34,200	29,700	25,100	29,900	35,900
CML 2 *baseline*	–	0.546	0.480	0.414	0.348	0.283	0.362	0.378

1 The Hierarchist perspective H/A is the version used in the Eco-indicator 99, where 'A' refers to the average weighting set and where Human Health and Ecosystem Quality Damages have been assigned 400 Points and Resources Damage has 200 Points.

tory tables including all input and output substances (raw material, airborne, water and soil emissions, and wastes) of all considered systems can be found elsewhere [14]. The amount of materials required for the water transfer (thousands of tons) is significantly higher than those required for desalting (tons) the same amount of water.

Table 3 shows some of the most relevant airborne emissions produced by the RO and the transfer along all their life cycle: accounting for natural resources required for their extraction, manufacturing process, the energy consumed for the operation of both alternatives, and so on. The electricity input for the RO and the transfer comes from Spanish average energy production scenario (its electricity production sources are: 51.3% thermal; 35.4% nuclear and 13.3% hydroelectric [15]). With the present state of the art of the RO technology (4 kWh/m^3), it is the more polluting alternative.

Analyzing the results presented in **Table 3**, in which different energy consumptions for RO are presented in agreement with the technological improvements that it is expected to reach in the mid-term [16], the strong influence of the energy consumption on the airborne emissions is clear. Similar results are obtained when analyzing the emissions of pollutants to other media (soil, water). As a consequence, the overall scores obtained for the whole LCA, using three different evaluation methods (see **Table 4**), in order to obtain a broader outlook and more rigorous and objective conclusions, reveal the same trend with respect to the energy.

The importance of energy can be better understood when the LCA results are presented in percentage from each life cycle stage, as shown in **Table 5**. In both options, the operation stage, in which the energy consumption is the more important factor because the infrastructure and the plants are already built, is clearly the most important phase. This result reveals that both options, RO and the ERWT, are energy-intensive consumers. Thus, the efforts for reducing the environmental load in both options should be devoted in the address of reducing the energy consumption and/or the usage of environmentally-friendly energy production systems.

In the case of RO, the environmental load corresponding to the materials (assembly and membranes), compared with the environmental load associated to the energy (operation phase), is very low. However, in the case of the ERWT, the impact associated with the assembly phase is higher, due to the important amount of materials required for the infrastructure.

Table 5: Environmental load for three different assessment methods, corresponding to each life cycle phase for the RO (4 kWh/m^3) and the ERWT considering the repayment periods of 25 and 50 years. The calculus base is 25,000 hm^3 fresh water for both systems

Process	Life cycle phase	Unit	EI 99	Ecopoints 97	CML 2 *baseline*
RO	Assembly	%	6.95	10.22	2.03
	Membranes	%	0.77	0.28	0.06
	Operation	%	92.28	89.05	97.91
	Final disposal	%	0	0	0
ERWT (50 years)	Assembly	%	19.09	20.32	4.50
	Operation	%	80.91	79.68	95.50
ERWT (25 years)	Assembly	%	31.58	33.60	8.58
	Operation	%	68.41	66.40	91.42

4.1.1 Analysis of energy consumption reduction in RO

During the last years, the RO desalination technologies have strongly reduced their energy consumption [5]. The use of energy recovery systems for RO allows for a significant reduction in the energy consumption. With the present technology, there are already small RO plants that consume 2 kWh/m^3 of desalted water [6,7]. In this context, it is a feasible scenario that this target or even lower energy consumption could be reached for big desalination plants, taking into account that the minimum theoretical work for desalting seawater is about 0.8 kWh/m^3, as already explained in Part 1. In Table 3, it is shown how the most relevant airborne emissions associated with RO for different energy consumptions are reduced by about 46% when the energy consumption is reduced, from 4 kWh/m^3 to 2 kWh/m^3. Table 4 shows the total scores considering different consumptions from the present (4 kWh/m^3) to the near future technology (2 kWh/m^3); with the three methods, the consumptions are reduced by about 45%. In the case of the ERWT, if the repayment period is 25, the total amount of materials is doubled, and this causes an increase of about 10% in the relevant emissions (see Table 3) and of about 20% in EI 99 and Ecopoints 97 methods, and about 4% in the CML 2 *baseline* method in the overall scores (see Table 4). The total score for the ERWT with 50 years of repayment period is in close-agreement with an RO consumption of 2.5 kWh/m^3 in the three methods. However, the environmental load of the ERWT with a repayment period of 25 years is similar to RO, with an energy consumption of 3 kWh/m^3.

4.1.2 LCA of RO and ERWT versus different energy production models

All previous results have been obtained considering that the electrical energy has been produced following the Spanish pattern considered in the BUWAL 250 database [15], which considers that 51.3% of the electricity produced in Spain comes from fossil fuels, 35.4% is produced in nuclear power plants and 13.3% in hydropower plants. Due to the importance of energy in both analyzed alternatives, desalination and water transfer, the evolution of environmental loads has been studied when modifying the technology of electricity production, in order to estimate the possible future trend of environmental loads of both alternatives depending on the energy model adopted in Spain in the mid or long term. Three different scenarios have been considered (see **Table 6**):

- The first one is nuclear electricity production dominant.
- The second one analyzes the effect of the massive use of renewable energies[2].
- Finally, an electricity production scenario based mainly on fossil fuels has been analyzed.

When comparing the RO desalination technology (considering 4 kWh/m^3) versus the ERWT (applying different electricity production scenarios), it is shown that the progressive substitution of fossil fuels, either by nuclear energy or by renewable energies, provokes a higher reduction of the environmental load of RO than that one corresponding to the water transfer. As a consequence, as shown in **Table 7**, the airborne emissions of RO are similar to those corresponding to the ERWT, in the case of a nuclear setting, and lower than those provoked by the water transfer in the case of an electricity production model based on renewable energies.

[2] Note that hydropower on a large scale is not considered strictly renewable due to the environmental load provoked by big dams; however, it was most appropriate for estimating the results of an electricity production mainly based on renewable energies.

Table 6: Electricity production models in different scenarios [15]

Origin	Unit	Spanish model	French model	Norwegian model	Portuguese model
Thermal (oil, gas, coal, lignite)	%	51.3	11.4	0.5	80.8
Hydropower	%	13.3	15.7	99.2	16.6
Nuclear	%	35.4	72.9	0.3	2.6

Table 7: Relevant airborne emissions produced by RO and transfer below different scenarios of electricity production

		kg CO_2 / m^3 prod. water	g dust / m^3 prod. water	g NO_x / m^3 prod. water	g NMVOC / m^3 prod. water	g SO_x / m^3 prod. water
Spanish model	RO	2.26	3.10	5.10	1.00	14.7
	ERWT (50 years)	1.44	2.02	3.58	0.77	7.25
	ERWT (25 years)	1.55	2.03	4.21	0.93	7.52
French model	RO	0.59	0.65	1.47	0.30	1.43
	ERWT(50 years)	0.39	0.41	3.58	0.77	7.25
	ERWT (25 years)	0.51	0.43	1.94	0.49	1.94
Portuguese model	RO	3.15	3.24	7.54	3.97	25.77
	ERWT (50 years)	1.99	2.11	5.11	2.63	14.18
	ERWT (25 years)	2.11	2.12	5.73	2.78	14.46
Norwegian model	RO	0.16	0.03	0.43	0.06	3.67
	ERWT (50 years)	0.13	0.017	0.67	0.18	0.36
	ERWT (25 years)	0.24	0.027	1.29	0.34	0.66

Table 8: Overall scores obtained by the analyzed RO and ERWT with different scenarios of electricity production. The calculus base is 25,000 hm^3 fresh water for both systems

		EI 99	Ecopoints 97	CML 2 *baseline*
		Gpoints	GPoints	–
Spanish model	RO (4 kWh/m^3)	2.62	43,400	0.546
	ERWT (50 years)	1.86	29,900	0.362
	ERWT (25 years)	2.20	35,900	0.378
French model	RO (4 kWh/m^3)	0.875	15,600	0.129
	ERWT (50 years)	0.719	11,700	0.088
	ERWT (25 years)	1.06	17,700	0.105
Portuguese model	RO (4 kWh/m^3)	5.02	69,200	0.591
	ERWT (50 years)	3.44	46,900	0.395
	ERWT (25 years)	3.78	52,900	0.411
Norwegian model	RO (4 kWh/m^3)	0.349	7,790	0.021
	ERWT (50 years)	0.373	6,590	0.017
	ERWT (25 years)	0.713	12,600	0.033

In the case of the complete LCA, the scores obtained with the different evaluation methods are shown in **Table 8**, and reveal the same trend: the environmental load associated with the RO, considering an energy consumption of 4 kWh/m^3, is similar or even lower than that corresponding with the ERWT, when the electricity production based on fossil fuels is reduced and substituted by nuclear and/or renewable energy.

4.1.3 Analysis of reducing the amount of transferred water

In the previous analysis, it has been considered that a maximum water volume (1,050 hm^3/year during 25 consecutive years) could be diverted from the Ebro River every year. However, this scenario can be considered very optimistic. Historical data [1] reveal that drought periods are very common in the Ebro Basin, and the effect of climate change and the possible future water demands in the Ebro Basin have not been considered either [17].

Thus, it has been analyzed considering the evolution of the environmental loads when the transferred water is lower than the maximum planned (1,050 hm^3/year), which is the most likely scenario in drought periods. As shown in **Table 9**, the environmental load associated with the water transfer increases when the amount of transferred water decreases due to the environmental loads associated with the materials that remain constant, independent of the amount of transferred water. This effect is more important in the evaluation methods EI 99 and Eco-point 97, because the materials have a higher influence in these methods than in the case of the CML 2 baseline. In the case of RO, this analysis is meaningless, because desalination does not depend on meteorological aspects.

As shown in **Table 9**, considering a repayment period for the ERWT of 50 years, it is obtained when transferring the 55% of total water amount so that the environmental load is similar to that of the RO with an energy consumption of 3 kWh/m^3. In the case of considering a repayment period of 25 years for the hydraulic work, the environmental load corresponding to a water transfer of 55% of the total amount is the same as in the RO when its energy consumption is 4 kWh/m^3. Similar results are obtained when applying the Eco-points 97 method. However, in the case of the CML method, the environmental loads corresponding to the ERWT are not very sensitive to the amount of transferred water. As already mentioned, the CML method gives a relatively lower weight to the material usage than in the other two methods employed. As a consequence, only when the energy consumption of RO is 2.5 kWh/m^3, the environmental load of RO is lower than that provoked by the ERWT when 70% and 100% of maximum volume are diverted (considering respectively 50 and 25 years of repayment period for the hydraulic work).

Table 9: Comparison of RO vs. ERWT as a function of different volumes of transferred water

	Unit	ERWT (50 years of repayment period)					
	%	100	90	80	70	60	50
EI 99	$kPoints/hm^3$	70.86	72.38	74.28	76.76	80.00	84.57
Ecopoints 97	$GPoints/hm^3$	1.139	1.168	1.200	1.241	1.295	1.371
CML 2 *baseline*	$(1/hm^3)\cdot10^{-6}$	13.79	13.89	13.95	14.04	14.16	14.40
		ERWT (25 years of repayment period)					
	%	100	90	80	70	60	50
EI 99	$kPoints/hm^3$	83.8	86.77	90.48	95.24	101.59	110.48
Ecopoints 97	$GPts/hm^3$	1.367	1.418	1.486	1.567	1.676	1.829
CML 2 *baseline*	$(1/hm^3)\cdot10^{-6}$	14.40	14.52	14.71	14.91	15.17	15.69
		RO desalination technology					
	kWh/m^3	4	3,5	3	2,5	2	
EI 99	$kPoints/hm^3$	104.80	93.02	81.60	70.00	58.04	
Ecopoints 97	$GPoints/hm^3$	1.736	1.552	1.368	1.188	1.004	
CML 2 *baseline*	$(1/hm^3)\cdot10^{-6}$	21.84	19.20	16.56	13.92	11.32	

5 Conclusions

In this paper written in two parts, the Life Cycle Analysis (LCA) has been applied to commercial water production technologies: in Part 1, the desalination technologies MSF, MED and RO have been compared and, in **Part 2**, the comparison between the ERWT and desalination has been presented, in particular comparing with respect to RO, which is the less aggressive commercial desalination technology for the environment, as has been proven in **Part 1**. The software SimaPro 5.0, which is structured as established phases by the standard ISO 14040 for LCA, has been used to conduct the analysis. Although the scope is general and not very detailed, the results obtained are significant enough in order to obtain a general outlook about the less aggressive water production technology for the environment. The main conclusion reached in the first part is that RO desalination technology presents a significantly lower environmental load than thermal processes (MSF and MED).

In this second part, the main conclusions reached are as follows:

The comparative LCA between RO and the ERWT reveals that both alternatives present similar environmental loads. Although the necessary energy to transfer the water from the Ebro River to the Mediterranean basins with the present technology is lower than for the RO desalination, the impact associated with materials for building the transfer infrastructures almost compensates for the difference. The results of the water transfer vary depending on the repayment period considered: when 25 years are considered instead of 50 years, the environmental load associated with the water transfer increases (about 20%) and the same occurs for the contribution of the assembly phase.

An energy consumption reduction associated with RO from actual 4 kWh/m^3 to 3–2.5 kWh/m^3, achieves similar total environmental load scores to that with the ERWT. Thermodynamics establish the minimum theoretical energy consumption for seawater desalination in less than 0.8 kWh/m^3 [18]. Taking into account the trend of the energy consumption reduction of desalination technology during the last 10 years [4,5,19], and the minimum thermodynamic limit, it seems a feasible target in the next 10 years to reach an energy consumption of large RO plants of 2.5–3.0 kWh/m^3. It is likely to be even lower since the energy consumption in RO desalination plants does not depend very much on its size and small RO plants with energy consumptions of about 2 kWh/m^3 have already been reported [6].

The previous results have been obtained considering the maximum amount of water transferred per year (1,000 hm^3/year). However, when the amount of diverted water decreases, the environmental loads associated with both options are very similar:

- When a repayment period for the ERWT of 50 years is considered (it is the scenario more favorable for the hydraulic work and less profitable for RO desalination): for about 55% of transferred volume, the environmental load associated with the ERWT is similar to RO when its energy consumption is 3 kWh/m^3.
- Considering an amortization period of 25 years for the ERWT (it is the more interesting scenario for RO): for about 55% of the transferred volume, the environmental load associated to transfer is similar to RO when its energetic consumption is 4 kWh/m^3 and the equality of environmental loads is 3.5 kWh/m^3 for about 75% of the transferred volume.

In respect to the potential reduction of environmental loads, these loads can be significantly reduced in both technologies when applying an energy production model based on renewable energies. The total scores and the airborne emissions obtained from an electricity production model based on renewable energies are about 80–85 times lower than those obtained when the electricity production model is mainly based on fossil fuels. However, the potential of technological improvement in the case of RO desalination – energy consumption with the new energy recovery systems in development can be reduced by 50% in the mid-term – is much higher than in the case of the water transfer, which is a mature technology with a low margin for technological improvement. It is important to remark that water transfer is an infrastructure conceived for supplying water during several decades and even centuries and, in this context, it is a very rigid solution.

From these results, it can be concluded that if the environmental load of RO is about the same order of magnitude as that provoked by the ERWT, with the present state of the art of technology, it is very likely that, when the infrastructure of the ERWT will be finished by 2010–2012, the LCA of reverse osmosis will clearly function against the transfer.

Note that previous conclusions have been reached considering only the materials and energy consumption of the two alternatives (RO desalination and ERWT) in the analysis.

Other environmental impacts that have not been included in the present work and that should be considered for a more detailed environmental assessment would be, among others:

- The effect on the Ebro River Basin of the extraction of the diverted water. This effect could be particularly important in the case of the ecosystem of the Ebro Delta, which is suffering from saline intrusion from the sea water due to the reduced amount of fresh water and sediments provided by the Ebro River.
- The effect of connecting isolated water basins, for instance, a) in terms of biodiversity particularly in the case of Spanish basins containing unique endemic species, b) in terms of propagations of invasive species as is the case for the Zebra mussel or c) in terms of propagation of pollutants dispersed in the Ebro River basin.
- The effect of the brine disposal, particularly in terms of biodiversity of the marine flora or in terms of local coastal impacts due to higher salinity provoked by the brine.
- The problem of quality of the transferred water, which is clearly lower than the desalted water that can be used for drinking, agricultural and industrial purposes. Transferred water would require an additional treatment for drinking purposes, that has not been considered in the analysis.

These late impacts, if considered, would benefit the RO scenario, except in the case of brine disposal. Moreover, it is noteworthy to remark that while the secondary water distribution network from the channel to the end-users is not considered in the EWRT option, a pipeline of 20 km from

each RO plant, to distribute the water obtained, has been included in the RO option. This assumption increases the final results of the LCA of RO desalination by about 10%-20% which can be estimated just by comparing the results of the LCA of RO obtained in Part 1 and Part 2 of the paper. This means that the analysis of RO in Part 2 has been made with very conservative assumptions that could be likely to overestimate its assessed environmental loads.

Additional considerations related with social impacts of both alternatives, which are out of the scope of the LCA technique, could also be formulated. The water transfer distributes these resources extracting them from another basin, thus provoking potential social tensions between different territories. However, the desalination alternative, without provoking any environmental impact in the Ebro River basin, produces the required water in the Mediterranean region with a similar or even a lower global environmental load in the mid-long term than the water transfer.

It is also important to note that big hydraulic works are usually strongly subsidized and the final user very often does not pay the real cost of producing the water. This is not the case of desalination, in which it is a common practice that the final user would pay the real cost of desalting the water. In this context, the ERWT would not help in the environmental education of people, because they cannot see the economic as well as environmental benefits of a better water management, i.e. saving water, appropriate maintenance of the water distribution network and so on.

From the results obtained in this two part paper, it can be stated, from the perspective provided by the LCA, desalination technology, that presenting a very important potential of reduction of the provoked environmental load can be considered a real and serious technological alternative to the solutions of water provision and management based on conventional big hydraulic works.

However, desalination is an energy intensive process, therefore, its future, as some other water supply alternatives, is linked to the problem of energy source availability, possible depletion of conventional energy sources and cost, as well as to the environmental impacts (including the trend to minimize the CO_2 emissions in order to reduce the greenhouse effect). Furthermore, the associated economic costs of desalination (investment and operation costs), which are sometimes higher than conventional water supply techniques, could limit its world expansion.

Therefore, desalination should always be considered after applying water 'demand' strategies to avoid water availability problems such as, for instance: efficient irrigation methods, reduction of leakages in pipes, use of water saving devices in households, introduction of water markets in drought periods, and the intensive use of reused water should previously be strengthened.

Desalination should be the selected water 'supply' alternative when provoking less economic and environmental charges to conventional alternatives for supplying water (other solutions may involve inter-basin transfers with a huge budget and uncertainties derived from the climatology). These environmental charges, as shown in Part 1 of this paper, can be dramatically reduced through process integration, particularly when properly integrating desalination technologies with other industrial processes from an energy viewpoint.

The authors of this paper are investigating this aspect and, since the preliminary results of their ongoing research work, it seems that there is a very interesting and promising future, particularly when integrating desalination with complex energy production systems.

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